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13. ABSTRACT (Maximum 200 words)

We report on research done on magnetic multilayers. We studied a variety of fundamental problems including:

1) Phase transitions -- Here we investigated how two different magnetic materials layered together could result in a new material with unique thermal and magnetic properties.
2) Here we studied the effect of a mixing region in the Giant Magnetoresistance Effect (GMR). We showed that the theory could describe experimental results well.
3) We also studied the spin wave spectrum of magnetic multilayers and saw how the spin waves could be used to characterize the exchange coupling between different materials.

Possible applications include the use of high frequency spin waves in signal processing at the 10-30 GHz range

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Statement of the Problems Studied

This project involved a general theoretical study of the magnetic, electronic and thermal properties of magnetic multilayers. The major areas of investigation were:

1) Thermal properties of magnetic multilayers -- phase transitions
2) Electronic properties of multilayers -- giant magnetoresistance
3) Magnetic properties of multilayers -- spin waves and electromagnetic response

Below we discuss each of the three areas in more detail.

Thermal properties of magnetic multilayers -- phase transitions
A normal material has a small number of surface atoms compared to the number of interior atoms. As a result, normal materials do not show significant surface effects. In contrast multilayer systems can be built where the number of surface or interface atoms is about the same as the number of interior atoms. This means that these materials can have very new and different properties from those found in nature. One fundamental question studied was in regard to the nature of the magnetic/nonmagnetic phase transition that occurs as the temperature is increased, i.e. if two different materials - with two different transition temperatures - are used in a layered structure, what is the transition temperature of the resulting material. This has important practical applications as well as being of interest theoretically. For example some materials which are of interest magnetically have transition temperatures at temperatures below room temperature. Thus if such a material could be thermally stabilized by coupling to a high temperature material it might be made useful.

2) Electronic Properties of Magnetic Superlattices -- Giant Magnetoresistance

The giant magnetoresistance (GMR) effect was discovered in 1989. This effect occurs in magnetic multilayers such as Fe/Cr or Co/Cu. In these structures there can be a large change in electrical resistvity as an external magnetic field is turned on. We note that this effect is now being explored for reading heads in hard disk systems and is likely to improve the density of stored data substantially.

We studied a number of important aspects of this effect. One key issue in GMR is the importance of scattering of electrons at interfaces. Previous calculations had been done under with assumptions of perfect interfaces. In reality, the interface is generally a region where both

materials are mixed together. We looked at the impact of this mixing region on the giant magnetoresistance.

A second question of significance was addressed in regard to the electronic properties. Much of the earlier work on magnetic superlattices use exchange interactions were treated simply as parameters. However it is important to determine the relationship between the true electronic structure of the multilayer and the resulting magnetic order. This is clearly an immense, yet important task. As an initial step in this direction we explored a model system, one dimensional Hubbard chains, through mean field theory and RPA.

3) Magnetic Properties of Multilayers -- Spin Waves

In recent years a lot of effort has been put into studying spin wave modes in magnetic multilayers. Of particular interest have been systems where ferromagnetic films couple antiferromagnetically to other ferromagnetic films through spacer layers. There are three key reasons for examining magnetic excitations in these systems:

1) Some long wavelength spin wave modes in these structures exist at double the frequency of the equivalent spin wave modes in ferromagnetic films. As a result these structures offer possibilities for signal processing at higher frequencies.

2) The magnetic spin configuration of these structures can be significantly changed by the application of modest external fields. A consequence of this is that the spin wave frequencies may also be varied over a wide range.

3) Systems with antiferromagnetically coupled ferromagnetic films (Fe/Cr/Fe) generally show the giant magnetoresistance effect. Therefore methods to probe the behavior of these systems are of interest in order to better understand (and use!) the GMR effect.

Summary of Most Important Results

1) Phase Transitions in Magnetic Superlattices

As discussed above, a basic question in the physics of superlattices is the following. One has a sequence of alternating layers of material, A. and B. If A and B are very thin layers, one has synthesized a new material. If each is, say, a ferromagnet, then there will be a single magnetic phase transition, at a temperature controlled by the magnetic couplings in A, those in B, and those at the interfaces. In the case where A and B are quite thick, there will be two orderings, one near the bulk ordering temperature of A, and one near that of B. In this case each film behaves like a bulk material, perturbed only weakly by interactions with neighboring films. We outlined, in theory, the nature of the response of superlattices in each regime, and the crossover between the two. We did this using the (mean-field) Landau-Ginzburg theory, and explored this question by calculating the temperature variation of the order parameter, along with the magnetic susceptibility.

We showed how the experimental results in antiferomagnetic superlattices (CoF_2/FeF_2) could be understood in terms of interface exchange coupling and film thickness. The key idea is that the coupling at the interfaces allows the material with the higher transition temperature to stabilize the material with the lower transition temperature. Since the stabilization only extends a few atomic layers away from the interface, this produces a significant effect for thin films, but only a small change for thicker films.

2) Electronic Structure and Giant Magnetoresistance

The origin of the giant magnetoresistance effect (GMR) is due to the spin dependent scattering of electrons, i.e. spin up electrons have a different mean free path compared to spin down electrons. Much of this scattering occurs at the interfaces between different materials. As a result our calculation of the GMR effect for systems with a "mixing layer" between the different materials is very important in order to make good contact with experiment. Our calculations were, in fact, able to give a very good description of how the giant magnetoresistance effect depended on the geometry of the layered structure, i.e. the dependence on the number of layers, the dependence on the materials and the dependence on the thicknesses of the different layers. These kinds of results are very important in order to use the GMR effect in an industrial setting.

As discussed above, we also investigated a model which connects the underlying electronic structure of the magnetic material to the parameters needed by more macroscopic descriptions of the magnetic system. With this model we found: 1) It requires more than 20 atomic layers for the

response of the layered structure to approximate the response of a collection of bulk-like films; 2) The onset of magnetic order produces a clear signature in the wavevector dependent susceptibility of the superlattice and 3) Modest changes (around 30%) in the strength of the electron-electron interaction results in significant changes in the magnetic order. Thus a major conclusion is that multilayer structures can be expected to display a rich magnetic behavior which is quite distinct from the character of any of the constituent materials.

3) Spin Waves

The theoretical calculation of spin wave modes in multilayers with complex spin configurations is quite challenging. In the past a number of approximate methods have been developed. Most promising of these is the effective medium method developed at UC Irvine and extended and applied to experimental results by the group at UCCS. A comparison of the theoretical results to Brillouin light scattering data for Co/Ru multilayers showed that effective medium theory was quite good. In particular, we examined the spin wave modes for a Co/Ru multilayer system which shows large antiferromagnetic coupling between the Co layers through the Ru films and compared theoretical and experimental results. This work was done in collaboration with a group in the RWTH in Aachen, Germany. A number of important results emerged:

1) Brillouin scattering could be used as a nondestructive test of the interlayer exchange coupling. We were easily able to observe the oscillations in exchange coupling between the Co films as a function of the Ru spacer thickness. We were further able to obtain good values for the strength of the exchange coupling.

2) The behavior of the spin wave modes predicted by the effective medium theory was verified experimentally. In particular, the system now has a surface mode which extends over a much larger frequency range. This might help in coupling these spin waves to lower frequency acoustic waves and thus make new devices possible.

This work also shows the strength of the collaboration between Colorado Springs and Irvine. The initial theoretical work on the effective medium theory was done at Irvine. The extension of the theoretical work to include anisotropy (necessary in the real materials) and the direct comparison to the experimental work was done by the Colorado Springs group together with the group in Aachen.

Despite this initial success of effective medium theory, it is fundamental to know where this theory breaks down and what features, which are not predicted or described by effective medium theory, can be expected in real systems. Furthermore the effective medium theory treats exchange and dipolar interactions only approximately and is not able to properly discuss the more complex structures found in finite multilayers. We therefore obtained a complete treatment for spin waves in arbitrarily canted structures which calculates both exchange and dipolar contributions exactly.

We found that the effective medium approximation was reasonable only for long-wavelength modes in a **uniformly canted** multilayer. For non-uniform canting (the normal situation) the effective medium theory breaks down and even the long wavelength modes are not properly described. Our work in this area was extended to double-layer systems and compared to recent experimental results from Carl Patton's group. We found that the complete theory could produce an excellent description of all the spin wave modes (and magnetically induced phase transitions) in the double layer systems.

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A. S. Carrico	--	Visiting Professor
J. Thomas	--	MS earned during project
B. L. Johnson	--	Ph.D. obtained (in part) under this project

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D. L. Mills	--	Principal Investigator
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Inventions Reported

none